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Waves in piezoelectric crystals for frequency control and signal processing

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Abstract

We give a brief survey of the types of acoustic waves that propagate in piezoelectric crystals, touching upon some of the most useful crystal cuts, and some of the practical structures currently used. Materials that may substitute for quartz are considered. Equivalent network structures are dealt with for the characterization of devices, and examples of typical responses achieved for bulk, surface, and shallow bulk configurations are given.

Introduction

Acoustic wave propagation in solids was first harnessed for frequency control purposes in 1922 when Cady constructed the first crystal oscillator. The main virtue perceived at that time was the very large Q that produced a narrow bandwidth and consequent high frequency stability. In the intervening years additional features were recognized vis à vis electromagnetic wave propagation; one of these is the favorable 100,000 to 1 velocity ratio that guarantees device miniaturization by this factor. Most recently the advent of surface acoustic wave (SAW) and shallow bulk acoustic wave (SBAW) devices, to be discussed further below, have brought about a revolution in signal processing capabilities, while the bulk acoustic wave (BAW) resonators that are successors to Cady's unit have continued to evolve to a very high level of sophistication. Table 1 briefly summarizes some of the chief merits of acoustic signal processing.

Table 1. MERITS OF ACOUSTIC SIGNAL PROCESSING

- REAL TIME, HIGH-SPEED PROCESSING CAPABILITY
- LARGE BANDWIDTH (HUNDREDS OF MHz) DIRECTLY AT RF/MWAVE
- COMPACT-SIZE/LOW WEIGHT
- RELATIVELY LOW-COST MONOLITHIC CONSTRUCTION
- LOW-POWER CONSUMPTION/PASSIVE
- ANALOG PROCESSOR/ELIMINATE A/D & D/A CONVERSION

In order to see how these features, and others, arise, we will briefly consider the propagation of acoustic waves in solids of various configurations, and see how the various wave types permitted by the structures are characterized. We will then focus on those waves most commonly used in practical devices. Space limitations unfortunately preclude an interesting comparison between acoustic and electromagnetic wave propagation in guiding structures.

Table 2 synopsizes the main types of acoustic waves that propagate in isotropic solid media having simple configurations. In contrast with the electromagnetic (EM) situation, three polarizations are permitted for plane waves in unbounded space; the EM case corresponds to the shear acoustic waves. The shear acoustic waves are categorized by reference to their polarization with respect to a horizontal surface; displacements along the surface are characteristic of SH waves; displacements along the surface normal are produced by SV waves. At the interface between two semi-infinite half-spaces an interfacial wave, comprised of an admixture of P and SV motions, can propagate when the contacting media have certain elastic and density relationships.

If one of the two semi-infinite media is replaced by a vacuum, the interface wave becomes a Rayleigh surface wave; it is comprised of a P+SV combination "glued" together by the traction-free interface. The Rayleigh SAW is the wave type overwhelmingly used for acoustic signal processing purposes at present. One of its great advantages is its accessibility at the surface of a device where the signal may be tapped and modified. SH waves cannot be bound by a traction-free interface. However, if the medium is not isotropic, but an anisotropic crystal which is piezoelectric, then the electromechanical coupling that exists between the SH mechanical motion and the electric field produced by the piezoelectric effect can lead to a bound wave at the interface.

Table 2. ACOUSTIC WAVES IN ISOTROPIC MEDIA

Configuration	Wave Type Supported	Name	Note
Unbounded	Pressure (P)	compressional, extensional longitudinal, dilitational	1/
	Vertically polarized shear (SV) Horizontally polarized shear (SH)	transverse, distortional, equivoluminal, shear	2/
Two unbounded half-spaces in welded planar contact	P+SV in each semi-infinite medium, coupled by interface	Stoneley	3/
Unbounded half-space	P+SV coupled by free surface	Rayleigh SAW	4/
	SH coupled to quasi-static electric field by free surface	Bleustein-Gulyaev SAW	5/
Unbounded half-space coated with layer of finite thickness, or unbounded half-space with normal density gradient	P+SV coupled by free surface and by material gradient normal to surface	Rayleigh-like Sezawa-like	6/ 7/
	SH coupled by material gradient normal to free surface	Love	8/
Laterally unbounded parallel plate	P+SV	Rayleigh-Lamb	9/
	SH	---	

Notes and Remarks: All interfaces are horizontal; u=displacement; k=propagation direction; sagittal plane contains k and surface normal; anisotropy doesn't affect generic wave types, but produces greater complexity; u usually not $\perp$ or $\parallel$ k, or in sagittal plane, except for special directions of k.

1/ u $\parallel$ k; similar to fluid pressure wave.
2/ u $\perp$ k; similar to transverse wave on tensed string & EM waves in unbounded media.
3/ u in sagittal plane; requires certain elastic and density relations be satisfied.
4/ u in sagittal plane; premier surface wave.
5/ u $\perp$ k; requires piezoelectric crystal (anisotropic).
6/ symmetric motion about layer mid-plane; u in sagittal plane.
7/ antisymmetric motion about layer mid-plane; u in sagittal plane.
8/ u $\perp$ k.
9/ See references 1 & 2.

Layered structures support waves that have attributes of both bulk and surface waves; P+SV motions are coupled by the material discontinuities and are closely related to plate waves described below. SH wave motion is supported by the material gradient that exists normal to the free surface of a layered structure, or by the gradual gradient that results from density changes as occur in the earth. The SH coupling by the piezoelectric effect is similar to that of Love waves, except that the electric field plays the part of the material gradient.

The final category listed in Table 2 is acoustic wave motion in elastic parallel plates. The two major types are SH waves, and a mixture of P+SV waves. These latter types are extensively used for bulk wave frequency control devices.

This paper will emphasize two types of wave motion in piezoelectric crystals, bulk waves in plates and surface waves on a planar substrate. The bulk waves in plates to be discussed are further broken down into the traditional thickness modes of plates, where at resonance the plate thickness is a multiple of a half-wavelength, and a newer type of wave called the shallow bulk acoustic wave, which propagates in SAW structures and has some of the SAW attributes.

Crystal cuts

Acoustic waves are established in piezoelectric crystals primarily for three reasons: 1) low losses, leading to very high Q values which in turn produce high frequency stability and high selectivity; 2) the piezoelectric effect, which permits direct transduction of acoustic waves from an electrical input signal. This effect was discovered one hundred years ago by P. and J. Curie; 3) zero temperature coefficient, which is a sine qua non for practical device performance. This last feature, the zero temperature coefficient (ZTC), was evolved in 1934 for BAWs in quartz plates, specifically the AT and BT cuts.

Figure 1 shows an idealized quartz crystal model, with a variety of crystal cuts that have been discovered over the years for various purposes. These examples are almost exclusively cuts having a ZTC. The ZTC normally exists in a relatively small temperature range, but adequately small deviations of 10 to 50 parts per million can be achieved over wide temperature ranges. Figure 2 provides examples of the typical frequency-temperature (f-T) behavior of the AT and BT cuts (BAW) and of the ST cut (SAW) of quartz.

In Figure 3 is portrayed the usual orientational conventions for quartz. The AT and BT cuts are singly rotated, but a locus of ZTC cuts exists, as given in the accompanying graph. The solid lines are for doubly rotated plates using the slower shear mode of BAW; the dashed line is for the faster shear mode BAW in doubly rotated cuts of quartz. The ST (SAW) cut is also shown on the graph; it is the Rayleigh wave analog of the AT BAW cut.

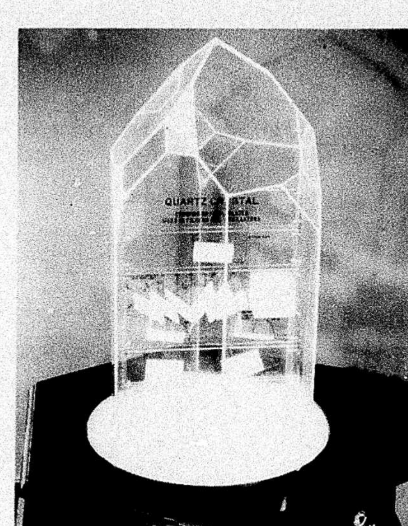

Fig. 1. Idealized Quartz Crystal with Cuts

New materials

The Curie brothers began their experiments using tourmaline - for which no ZTC cuts exist; quartz later showed its superiority, in this regard, and also because of its greater homogeneity. Until fairly recently very few of the many piezoelectric crystals tested were found to have appreciable applications potential. One exception is lithium niobate which has a large piezoelectric coupling factor and low loss, but no ZTC; its uses are largely limited to wide band SAW devices where the temperature coefficient is not a serious drawback. On the horizon are such new piezoelectrics as alpha aluminum phosphate (berlinite) and gallium arsenide. Figure 4 compares the squares of the coupling factors of quartz and aluminum phosphate, a quartz isomorph, for singly rotated cuts. Not only is the berlinite coupling higher than that of quartz, but this material does possess a locus of ZTC similar to that of Figure 3.[3]

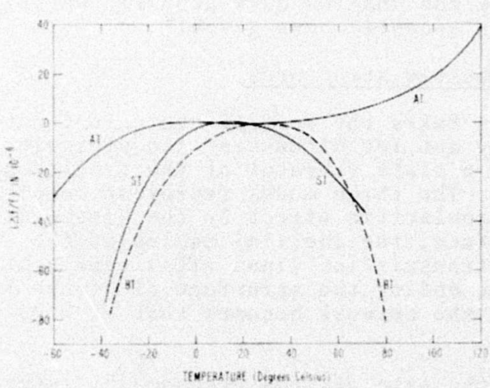

Fig. 2. Frequency-Temperature Comparisons

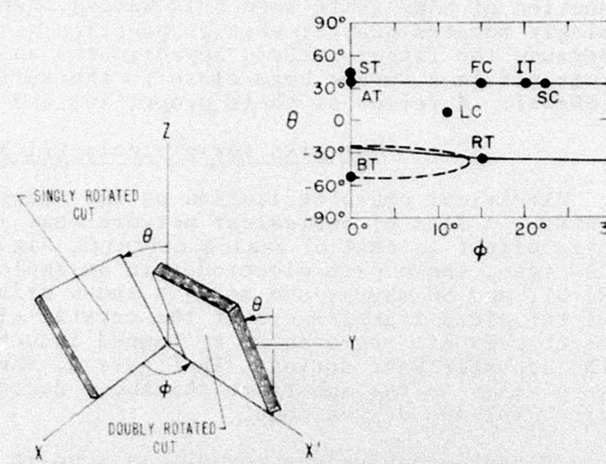

Fig. 3. Quartz Cuts and Zero Temperature Coefficient Loci

Gallium arsenide and other 2-6 and 3-5 semiconductors in crystal class $\bar{4}3m$ are piezoelectric. High resistivity regions can be used for the generation of acoustic waves, and their reception. These waves can be used to modulate active semiconductor devices in the future.

Configurations for generating acoustic waves

Figure 5 shows the physical construction of a BAW composite resonator. The quartz is used here solely as a high Q substrate, whereas the CdS thin-film layer is one half wavelength thick (approximately) at resonance. This configuration produces a comb of resonances in radar applications, e.g.; if the CdS and top electrode are removed, and an electrode is placed under the quartz, then the BAW structure becomes a thickness mode plate resonator, as used for high precision frequency control.

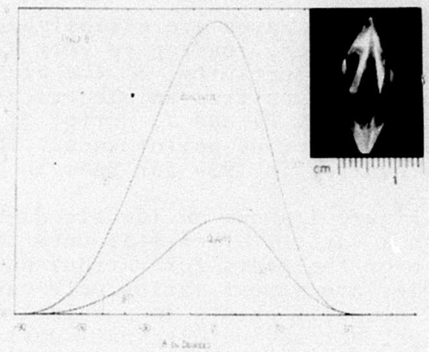

Fig. 4. Crystal Berlinite; k^2 Compared to Quartz

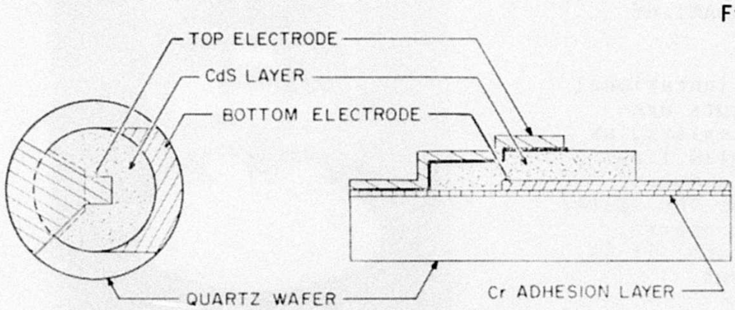

Fig. 5. Geometry of Bulk/Composite Resonator

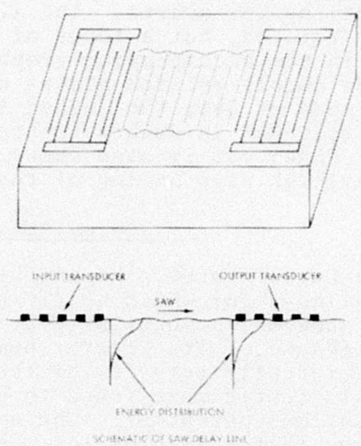

Fig. 6. Schematic of SAW Device

The interdigitated finger arrangements shown at the input and output of the structure in Figure 6 generate and detect SAWs, whose energy distribution with depth is given. The piezoelectric forces arise from the electric field gradients and peak sharply along the finger edges. Depending on what orientation in the crystal is being used, and what piezoelectric constants exist, the interdigital structure can produce bulk acoustic waves in addition to, or in place of, SAWs. A case in point is the production of SAWs (with some bulk waves) when the propagation direction is along the X axis in singly rotated quartz; when propagation is along Z', then only bulk waves are produced. Because the finger pattern approximates an end-fire antenna at resonance, the bulk waves come off in a narrow beam close to the surface; these are the shallow bulk acoustic waves (SBAWs). A review of their properties and literature has recently been given.[4]

Networks for piezoelectrically driven acoustic structures

Electrical characterization of the acoustic structures takes the form of equivalent networks. A form of equivalent network that is particularly apt for discussing the piezoelectric effect is that of analog circuits. Figure 7 portrays a plate vibrator of the traditional BAW type, shown with electrodes in an exploded position. The three modes represent coupled P, SV, and SH waves; one mode is shown driven by the piezoelectric effect by the placement of the piezo transformers at the crystal-electrode interface; the inertial masses of the electrodes are represented by lumped inductors, and the transmission lines (TLs) represent the acoustic wave motion. In Figure 8, the network representing the structure of Figure 5 is given. As the substrate thickness decreases to zero, the network becomes that of Figure 7 for one driven mode.

An analog equivalent network is seen in Figure 9 for the case of SAWs produced by interdigital fingers. The piezoelectric transformers are placed at the electrode edges; the laterally propagating SAWs are represented by waves on the TLs. The acoustic velocity and impedance vary depending upon whether or not the wave travels in the electroded or unelectroded regions. The circuit of Figure 9 also describes SBAWs, except that the TLs must vary in properties with lateral distance to account for the spreading of the SBAW beam.

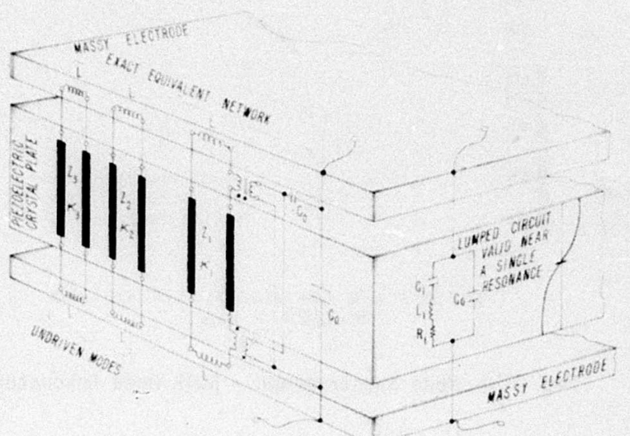

Fig. 7. Analog Network for Piezoelectric Crystal

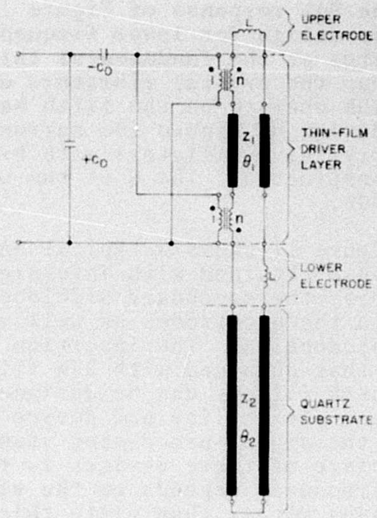

Fig. 8. Network for Bulk/Composite Resonator

Additional networks for acoustic wave propagation are given by Oliner, et al.[6,7]

Typical device responses

We turn now to a consideration of typical responses to be anticipated from BAW, SAW and SBAW devices. Figure 10a gives a plot of input admittance versus frequency for a thickness mode plate vibrator such as the one shown schematically in Figure 7. In measuring this spectrograph, the static capacitance Co has been balanced out. From Figure 10a one sees the high degree of frequency selectivity obtained for AT cut units. Also present in the mode spectrograph are secondary, unwanted, responses that would render this unit unfit for filter application. Even for fixed-tuned oscillators the presence of strong unwanted responses sometimes leads to mode jumping.

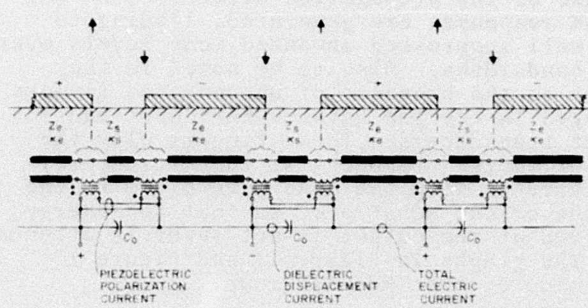

Fig. 9. Transmission-Line Network for Interdigital Electrodes

These unwanted resonances are caused by propagation of laterally travelling anharmonic overtones of thickness shear and thickness twist modes. Their suppression and control has been found to depend strongly upon the size and thickness of the driving electrodes. The crystal with electrode layer is treated as an acoustic cavity, with the uncoated surrounding crystal acting as an acoustic waveguide beyond cutoff for the desired main mode. The waveguide dimensions are arranged, however, so that for the undesired modes, propagation is allowed; this leads to their dissipation at the plate lateral boundaries. Such a resonator is described as "energy trapped." An example of one similar to the untrapped design of Figure 10a is given in Figure 10b. This BAW resonator is suitable for both oscillator and discrete filter use. The discrete filters fabricated from such resonators can be extremely narrow band, as is required for SSB applications.

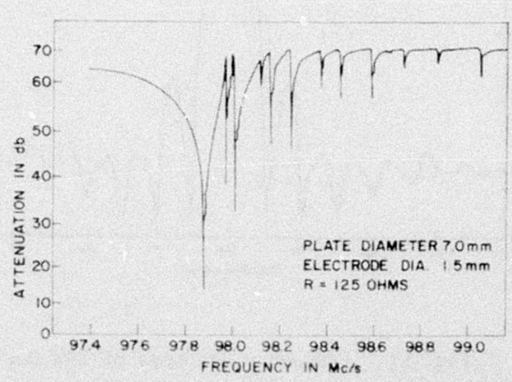

Fig. 10a. Bulk Mode Resonator With Complicated Spectrum

The BAW response of Figure 10c is a trapped energy design for lower frequencies. It operates at the fundamental thickness harmonic, whereas the crystal vibrators of Figures 10a and 10b operate on the fifth harmonic. With the design of Figure 10c narrow band filters and crystal oscillators with high stability may be constructed. The Q of the unit is about 200,000.

Figure 11 shows a typical SAW filter response obtained with interdigitated fingers; the secondary sidelobe patterns are due to the electrodes as well as to undesired BAW production. The insertion loss is greater than that obtained with BAW filters, but SAW and SBAW filters can be designed with much greater flexibility and device performance from the signal processing standpoint. Another advantage of these devices is that the operating frequency depends on the electrode finger spacings rather than plate thickness, so that use of submicron photofabrication procedures results in units in the GHz range.

In Figure 12 the response characteristic of an SBAW device on ST cut quartz is given. Because of the propagation direction, no SAW or BAW responses are generated, leading to very well suppressed unwanted mode levels over wide bandwidths. Also to be noted in the figure is the presence of unconnected fingers arranged in the gap between the input and output transducers. These fingers play the part of energy trapping for this structure, and serve to keep the SBAW wave close to the surface of the substrate, so that the energy received at the output is not severely attenuated. The graphs in Figure 11 and Figure 12 were made by the TRW SAW group.

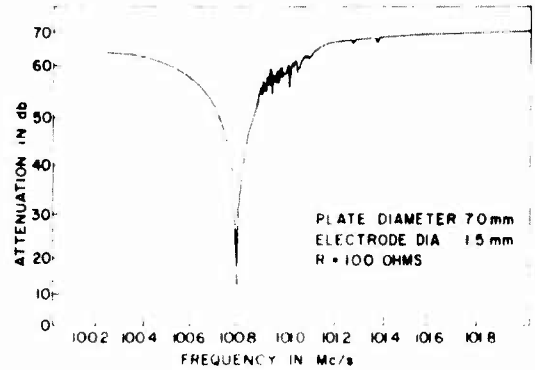

Fig. 10b. Mode Spectrograph - Bulk Mode Resonator

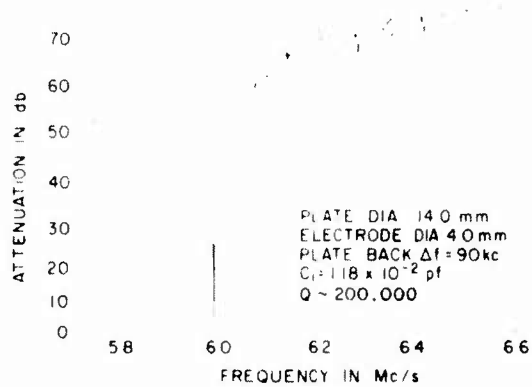

Fig. 10c. Mode Spectrograph - High Q BAW Device

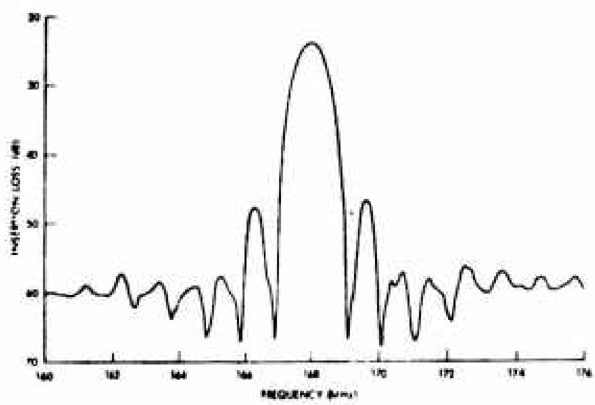

Fig. 11. Frequency Response of SAW Device

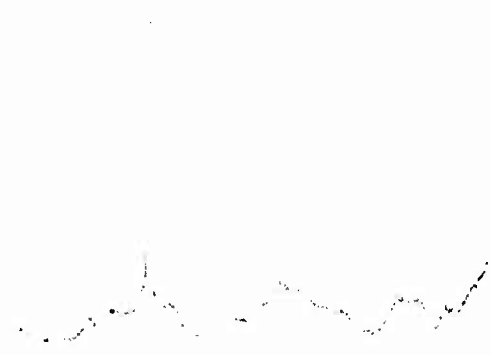

Fig. 12. Frequency Response of SBAW Device

Capabilities of BAW, SAW and SBAW devices

Based upon actual experimental data recorded to date, we give a brief summary of demonstrated capabilities for SAW and SBAW devices in Table 3. It should be noted that not every capability is present in a particular device. These are typical figures for 1980, and the prospect is excellent that they will be improved significantly in the future.

Table 3. DEMONSTRATED SAW/SBAW CAPABILITIES

CENTER FREQUENCY	60 MHz TO 2.3 GHz
FRACTIONAL BANDWIDTH	0.3% TO 2% (QUARTZ), 15% ($LiTaO_3$)
INSERTION LOSS	13 dB
SIDELOBE SUPPRESSION	>55 dB
SHAPE FACTOR 3 dB/40dB	1.4
TEMPERATURE COEFFICIENT OF DELAY	ZERO FOR FIRST ORDER COEFFICIENT

Table 4 provides some operating characteristics of high stability BAW oscillators, both present-day numbers and those projected to be achieved within the next decade. The performance improvements will come about largely by the use of the doubly rotated SC cut quartz vibrator, which has cancellation of the nonlinear elastic constants that produce frequency shifts when the vibrator is subjected to certain environmental stresses. High vacuum processing and ultraclean fabrication procedures will also be necessary to achieve the 1990 guesstimate figures.

Table 4. HIGH STABILITY BULK WAVE OSCILLATORS

		1980	1990 GUESSTIMATE
STABILITY:	1 SEC	1 pp 10^{12}	pp 10^{14}
	24 HOURS	2 pp 10^{11}	pp 10^{13}
	5 YEARS	5 pp 10^{8}	pp 10^{10}
	RETRACE	pp 10^{9}	pp 10^{11}
	ACCELERATION	1 pp 10^{9}/g	pp 10^{12}/g
	RADIATION	2 pp 10^{12}/rad	pp 10^{15}/rad
	-40 TO +75°C	5 pp 10^{10} (to 60°C)	pp 10^{12}
WARMUP		2 pp 10^{8} in 1 hour	pp 10^{10} in 1 min
POWER AFTER WARMUP, at -40°C		≈ 3 W	<250 mW
SIZE		>400 cm^3	10 cm^3
PRICE IN QUANTITY (1980 $)		>$1,000	<$300

Applications

Some idea of the range of frequency control and signal processing applications may be gotten from the entries in Table 5. Most of the uses listed there pertain to SAW and SBAW devices. The high stability, high precision uses of stress compensated BAW resonators will find future applications in systems such as JTIDS, GPS, NIS, SINCGARS, & SEEKTALK.

Table 5. APPLICATIONS FOR SELECT MILITARY SYSTEMS

DEVICES	FUNCTION	SYSTEM
BP FILTER; OSC	MAN-PACK REC	GPS
DELAY LINE	MORTAR LOC RADAR	TPQ 36
BP FILTER	VHF/UHF COMM REC	SINCGARS
HI-STAB OSC/SYN	TAC INFO DIST SYS	PACKET RADIO
OSC/BP FILTER/SYN	TACTICAL COMM	JTIDS - CLASS 2&3
OSCILLATOR	ARMY RADIOSONDES	AN/AMT-4D AN/AMQ-22 (XE)

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